Receiver performance characterization for modulating retro-reflector atmospheric optical links with pulsed lasers and optical pre-amplifiers

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Abstract

Receiver performance is calculated for two types of free-space atmospheric optical communications systems – a direct detection system using a p-i-n photodiode preceded by an optical amplifier, and an ideal coherent receiver operated in its shot-noise limited regime without an optical pre-amplifier. The signal format for both is amplitude shift keying (on-off modulation) with an assumed rectangular light pulse of duration T seconds. The more accurate Beckman probability density function (pdf) is used to describe the intensity fading rather than the more commonly used log-normal pdf which overestimates receiver performance. A coherent receiver using asynchronous detection is shown to outperform the direct detection system with an optical pre-amplifier gain of 30 dB by anywhere from 7 to about 10 dB depending on Rytov variance intensity fading levels. In addition, the effect of inner scale turbulence parameter, l_0, on system bit error rate is demonstrated.

Keywords: Atmospheric optical communication, atmospheric turbulence, free-space optical receiver performance

1. INTRODUCTION

Propagation losses in folded-path free-space optical communication links that employ modulating retro-reflectors increase as the fourth power of one-way link distance as opposed to distance squared for one-way point-to-point links [1],[2]. It is therefore necessary to maximize receiver sensitivity to make these types of folded-path links effective. This is accomplished here by using high peak power rectangular laser pulses of duration *T* seconds where *T* is very short compared to the time scale of the atmospheric turbulence induced intensity fading. The relatively slow modulating retro-reflector is assumed to modulate the amplitude of only one return light pulse for each digital information bit sent. The signal format is amplitude shift keying (ASK) or ON-OFF signaling if the modulator has a very high extinction ratio. The receiver analyses presented apply equally well to one-way point-to-point links as they assume only that the return pulse is not broadened in time and contains $n_{ST}\hat{I}$ signal photons. Here $\hat{I}$ represents a normalized intensity fading variable with unit mean and probability density function $P(\hat{I})$ and n_{ST} is the average number of signal photons contained in the atmospherically faded received light pulse. The receiver structures investigated consist of a direct detection receiver as shown in Figure 1. An asynchronous coherent receiver is shown in Figure 2 and is assumed to have a local oscillator laser sufficiently strong that the receiver operates in the shot-noise limited regime. No optical pre-amplifier and optical filter is required under these conditions. Both systems are assumed to have unit quantum efficiency p-i-n photodiodes as photodetectors and additive thermal noise due entirely to their load resistors.

It has long been known that atmospheric fading can not be accurately modeled under all conditions with a log-normal pdf for $P(\hat{I})$ except for conditions of very weak turbulence due to either very short optical path lengths, generally much less than a kilometer, or very stable air ($C_n^2 < 10^{-15} m^{-2/3}$). Section 2 describes conditional bit error probabilities for the two types of receivers. Section 3 presents a detailed description of Beckman pdfs that describe the intensity fading and their relation to the traditional log-normal pdf. Section 4 presents bit error rates as a function of turbulence strength and inner scale effects for both types of receivers and Section 5 presents some concluding remarks.

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14. ABSTRACT
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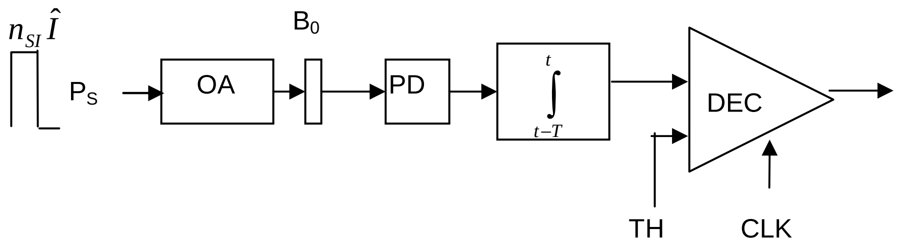

Fig. 1. Direct detection receiver consisting of an optical pre-amplifier (OA) with gain G and population inversion factor n_{SP}, optical filter with bandwidth B_0, p-i-n phododiode (PD) with 50 ohm load resistor, matched filter in the form of a moving integrator, and a clocked comparator as a decision circuit (DEC).

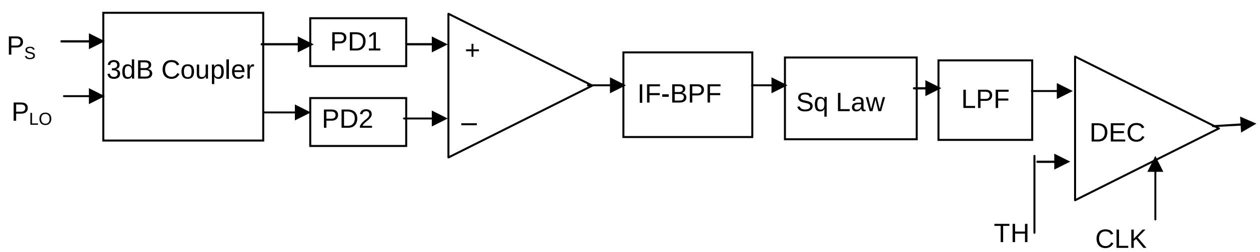

Fig. 2. Balanced detector coherent receiver for asynchronous (incoherent) ASK signal detection.

2. RECEIVER ANALYSIS

The use of an optical preamplifier in direct detection receivers can improve receiver sensitivity by 20 dB or more because it improves the electrical signal-to-noise ratio of the photodiode output photocurrent which contains large amounts of thermal noise [3]. The optical amplifier can not improve an optical signal-to-noise ratio, because of the amplified spontaneous emission (ASE) noise added by the amplifier, and would actually degrade receiver performance if an ideal photodiode with no additive thermal noise were to be used. The improvement comes from the fact that the largest component of the electrical noise becomes the ASE-signal beat noise as the optical amplifier gain and received signal levels increase. The optical amplifier also changes the photon statistics of the input light beam. A quantum mechanically correct description of the light amplification process [3] reveals that the initially Poisson statistics of a single input laser light pulse are changed to those of a Laguerre (or noncentral negative binomial) probability law at the output due to the ASE noise of the optical amplifier.

The statistics of the photocurrent output of the photodiode are modeled as Gaussian with a mean and variance derived from the Laguerre probability law for the number of photons output by the optical amplifier. In terms of the average number of photons input to the optical amplifier, n_{ST}, the means and variances under the two signaling hypotheses are:

$$m_1 = Gn_{ST}\hat{I} \qquad (1a) \qquad\qquad m_0 = \varepsilon Gn_{ST}\hat{I} \qquad (1b)$$

$$\sigma_1^2 = Gn_{ST}\hat{I} + B_0T[n_{bT}G + n_{SP}(G-1)] + B_0T[n_{bT}G + n_{SP}(G-1)]^2 + 2Gn_{ST}\hat{I}[n_{bT}G + n_{SP}(G-1)] + \frac{2KT_0}{e^2R_L}T \qquad (1c)$$

$$\sigma_0^2 = \varepsilon Gn_{ST}\hat{I} + B_0T[n_{bT}G + n_{SP}(G-1)] + B_0T[n_{bT}G + n_{SP}(G-1)]^2 + 2\varepsilon Gn_{ST}\hat{I}[n_{bT}G + n_{SP}(G-1)] + \frac{2KT_0}{e^2R_L}T \qquad (1d)$$

In Eqn (1), G is the optical amplifier gain and ε is the modulator extinction ratio, which is zero for perfect ASK signaling. The five terms on the right hand sides of the expressions for the variances are, respectively, signal shot noise, ASE shot noise, ASE-ASE beat noise, ASE-signal beat noise, and thermal noise due to the photodiode load resistor. The quantity B_0T represents the number of temporal modes passed by the optical filter. Ideally, this should be one, i.e. the optical filter bandwidth should be matched to the signal bandwidth, but this is usually not possible because of the difficulty in producing low insertion loss very narrow bandwidth optical band pass filters. The optical amplifier is assumed to be a single mode fiber coupled device operated in an unsaturated, linear gain regime with noise figure $F = G^{-1} + 2n_{SP}(G-1)/G$. The best that can be obtained is F = 3dB which occurs at high gain and $n_{SP} = 1$. The quantity n_{bT} represents the number of background light photons input to the optical amplifier and $n_{ST}\hat{I}$ is the number of signal photons actually coupled into the single mode fiber amplifier. Coupling losses for atmospherically faded laser light can be severe [4],[5] and can exceed 10 dB or more in the absence of optical phase front correction prior to coupling into the optical fiber input. The receiver does not contain a polarization filter following the optical filter because some retro-reflector modulators alter the polarization state when their reflectivity changes.

Under the restrictions of equally likely binary signals and equal false alarm and miss probabilities, the conditional bit error rate (CBER) for the receiver of Figure 1 is given by eqn (2) where erfc(-) is the complimentary error function [6]

$$CBER = \frac{1}{2} erfc\left(\frac{1}{\sqrt{2}} \frac{m_1 - m_0}{(\sqrt{\sigma_1^2} + \sqrt{\sigma_0^2})} \right) \qquad (2)$$

The system BER is obtained by averaging (2) over the normalized intensity fading variable, $\hat{I}$. For log-normal fading, $\hat{I} = \exp(2\chi)$ where χ is a Gaussian random variable with mean $-\sigma_\chi^2$ and variance $\sigma_\chi^2 = 0.124 k^{7/6} C_n^2 L^{11/6}$, the expression for the Rytov variance for a spherical wave under the assumption of a Kolmogorov spectrum [7]. Under this model, intensity scintillation saturation is included by limiting the maximum value of σ_χ^2 to 0.5, irrespective of the values of path length and refractive index structure constant. Reference [8] presents BER results for a variety of direct detection receivers using this approach. Here, we will use a Beckman pdf for the intensity fading statistics.

For the coherent receiver of Figure 2, maximum sensitivity is obtained through receiver operation in the shot noise limited regime which can be accomplished by using a sufficiently strong local oscillator laser. Therefore, no optical preamplifier is required. Nevertheless, in systems with insufficient local oscillator laser power, the use of optical preamplifiers to boost both signal and local oscillator optical power levels has been studied [3], [9]. Results indicated that improvements in receiver sensitivity (relative to a system with just a low power local oscillator) of many dB can be obtained for some phase or frequency modulation formats with the improvement due to a saturation in signal-to-noise ratio with optical amplifier gain. Here, we will assume that the local oscillator is sufficiently strong to obtain shot-noise limited operation and that $n_{ST}\hat{I}$ photons are coupled into the coherent receiver by the 3dB coupler. The CBER for the asynchronous ASK coherent receiver of Figure 2 is given approximately by the following expression [10] which is used to provide an approximate assessment of the performance difference between the two types of receivers.

$$CBER_{CASK} = 0.5 \exp(-(1/2) n_{ST} \hat{I}) \qquad (3)$$

3. BECKMAN PROBABILITY LAW FOR INTENSITY FADING

Over the years, there has been a number of probability density functions proposed to characterize the statistics of intensity fluctuations caused by atmospheric turbulence [11]-[14]. The log-normal pdf works very well under conditions of weak turbulence ($\sigma_{\hat{I}}^2 << 1$) but is not accurate under conditions of strong or saturated turbulence ($\sigma_{\hat{I}}^2 \geq 1$). Recent experimental measurements and simulations using phase screens [11],[15] have revealed that the Beckman probability law, denoted by $P_B(\hat{I})$, accurately characterizes both regimes. Under weak turbulence, it approaches the form of a log-normal pdf and under strong turbulence it approaches the form of the log-normally modulated exponential (LNME) density found by Churnside and Hill [13]. The Beckman pdf derives its name from the work of Petr Beckman who found a pdf for the amplitude of a wave propagated through a random medium [16]. This density gives the statistics of normalized intensity fluctuations at a single point in space. Aperture averaging with a lens of diameter substantially larger than the intensity fluctuation correlation length reduces the scintillation level and, if reduced to a sufficiently small value, the statistics of the aperture averaged intensity fluctuations again become well described by a log-normal pdf.

The properties of the Beckman pdf are well described in [11] and [17]. They are summarized below.
The Beckman pdf is obtained by averaging a Rice-Nakagami, density, $P_{RN}(\hat{I})$, with parameter R against a dimensionless random variable z that has a log-normal pdf, $P_{LN}(z)$, with parameter σ_z^2 which IS NOT the variance of $\ln(\hat{I})$ except for very large values of R, generally larger than 100. These quantities are given by [11],[17]:

$$P_{RN}(\hat{I} \mid z, R) = \frac{R+1}{z}\exp\left(-R-(R+1)\hat{I}/z\right)I_0\left(\sqrt{4R(R+1)\hat{I}/z}\right) \tag{4a}$$

$$P_{LN}(z \mid \sigma_z^2) = \frac{1}{\sqrt{2\pi\sigma_z^2}\,z}\exp\left(-[\ln z + \frac{1}{2}\sigma_z^2]^2/2\sigma_z^2\right) \tag{4b}$$

$$P_B(\hat{I} \mid R, \sigma_z^2) = \int_0^\infty P_{RN}(\hat{I} \mid z, R)P_{LN}(z \mid \sigma_z^2)dz \tag{4c}$$

where $I_0(-)$ is the modified Bessel function.

The values of the parameters R and σ_z^2 can be found from the statistical averages $<\ln(\hat{I})>$ and $<\hat{I}^2>$ determined either from actual measurement data or computer simulation using phase screens through the equations [11],[17]:

$$2E_i(R) + \ln\left(R^2(R^2+4R+2)\big/(R+1)^4\right) = 2<\ln\hat{I}> + \ln(<\hat{I}^2>) \tag{5a}$$

$$\sigma_z^2 = \ln\left(<\hat{I}^2>(R+1)^2\big/(R^2+4R+2)\right) \tag{5b}$$

where E_i(R) is the exponential integral function. The phase screen simulations were done for diverged waves that began as spherical waves and propagated through homogeneous atmospheric turbulence [11]. Under conditions of very weak turbulence, $\sigma_{Rytov}^2 = 4\sigma_\chi^2 = \sigma_{\ln\hat{I}}^2 = -2<\ln\hat{I}>$ and the pdf for $\hat{I}$ is essentially lognormal. At higher turbulence levels, the Rytov variance was found to be given by a more complicated expression dependent on the ratio of inner scale length to Fresnel zone size, l_0/R_F, where $R_F = \sqrt{L/k}$. The pdf for $\hat{I}$ was found to be the Beckman pdf of eqn (4). At very large, or saturated turbulence levels, values of R and σ_z^2 could not be found from eqn (5) and the pdf became the LNME density obtained by replacing the Rice-Nakagami density of (4a) with the exponential density $z^{-1}\exp(-\hat{I}/z)$ and averaging over the log-normal pdf as in (4c). The LNME pdf was verified by experimental measurements of a Gaussian laser beam propagated over a 1 km path 2 m above flat, uniform grassland [13].

The essential distinguishing feature between the log-normal and Beckman or LNME densities is that $P_{LN}(\hat{I}=0)=0$, whereas as for both of the other two densities $P_{B,LNME}(\hat{I}=0)>0$. The communication link BER is determined by the statistics of the intensity fading. At low values of BER, it is the leading shoulder of the pdf for $\hat{I}$ that completely determines system performance.

The results of [11],[17] are summarized in Figures 3 and 4 below which are 3D plots of *R* and σ_z^2 with l_0/R_F and σ_{Rytov}^2 as parameters.

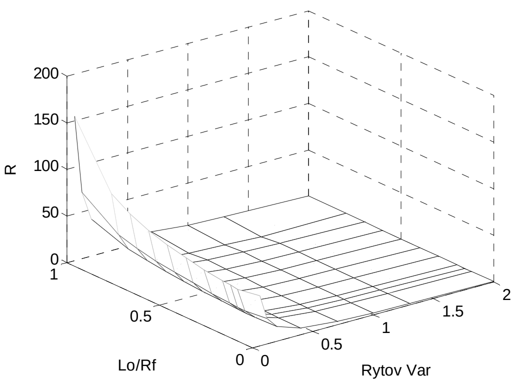

Fig. 3.

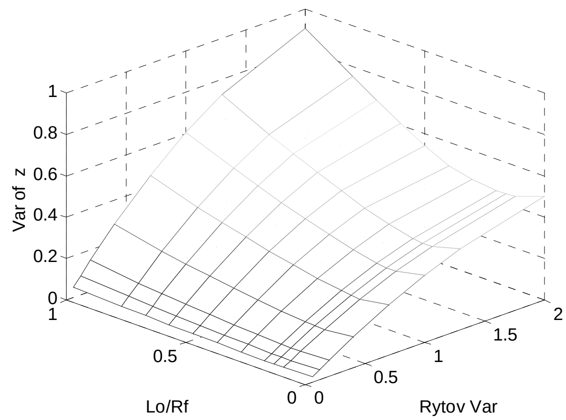

Fig. 4.

The pdfs are almost log-normal for very small values of $\sigma_{Rytov}^2 \le 0.06$ and large values of $l_0/R_F > 1.0$, which generally means short path lengths. Figure 5 illustrates an example. Figure 6 shows the exponential character of the Beckman pdf. In both plots, the comparisons with log-normal pdfs are most clearly shown by plots of the pdf($\ln\hat{I}$) scaled by $\sigma=\sqrt{\sigma_{\ln\hat{I}}^2}$ as in [11],[17].

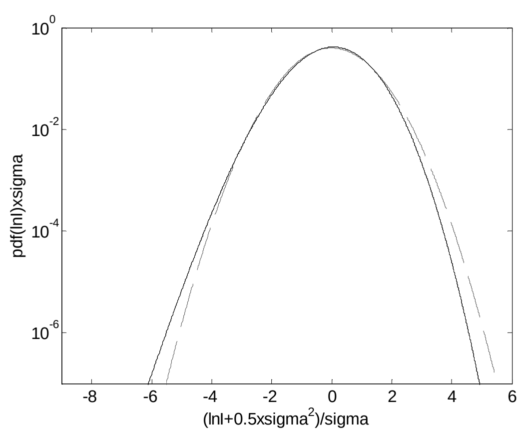

Fig. 5. Beckman pdf (solid line) and log-normal pdf (--- line) for l_0/R_F =0.5, σ_{Rytov}^2 =0.06, σ_z^2 =0.0286, R=62.6, and $\sigma_{\ln\hat{I}}^2=0.06$.

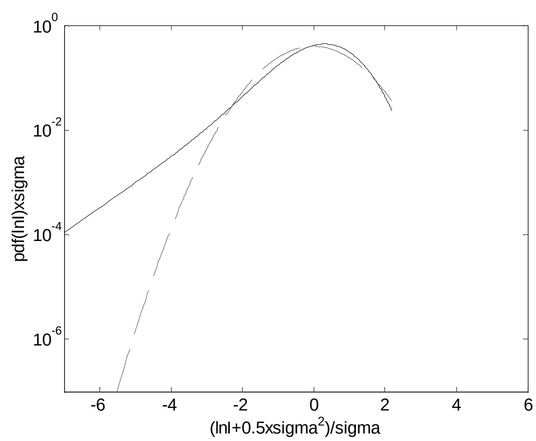

Fig. 6. Beckman pdf (solid line) and log-normal pdf (--- line) for l_0/R_F =0.5, σ_{Rytov}^2 =1.0, σ_z^2 =0.393, R=2.72 and $\sigma_{\ln\hat{I}}^2=1.18$.

4. RECEIVER PERFORMANCE

The performance of both types of receivers was determined by numerically averaging the CBER expressions (2) and (3) over the intensity fading using the Beckman pdf. The Beckman pdfs were numerically computed as in (4c) by integrating over a range in z of twenty standard deviations, centered about the mean of z, of the log-normal density, (4b). Comparison of these densities with those reported in [11],[17] gave excellent agreement for values of R < 80 and all values of σ_z^2. As an additional accuracy check, the performance of the direct detection receiver was computed assuming purely log-normal intensity fading for the same sets of parameter values as in [8] and found to give identical results. Receiver performance depends critically on the system parameters used in the mean and variance expressions, eqns (1). The function of the optical amplifier is to over ride thermal noise and render the signal-ASE beat noise the dominant term in the variance expressions (1c) and 1(d). The erfc(-) is a decreasing function of its argument which increases with the value of $n_{ST}\hat{I}$ and eventually becomes independent of optical amplifier gain, G. Receiver sensitivity improvement therefore "saturates" with G and an optical gain of G = 30dB is enough to obtain all but the last one or two dB of increase in receiver sensitivity. All calculations here and in [8] were performed with G = 1000.

The following parameter values were used in the computations of receiver performance in order to determine optimal performance for a realistic pulsed laser communication link at the fiber optic telecommunications wavelength of 1.55μm. The number of temporal modes input to the amplifier was set at 100 to represent the use of a 100 Ghz optical bandpass filter and 1 ns duration laser pulses. The optical amplifier was assumed ideal, with n_{SP} =1 and the modulator extinction ratio was assumed perfect, ε = 0. A 50 ohm load resistor at an effective noise temperature of 300 K was assumed. Receiver BERs were computed using a simple Simpson's rule numerical integration as

$$BER = \int_a^b CBER(\hat{I})P_B(\hat{I})d\hat{I} \qquad (6)$$

with the limits, *a,b* determined by the value of the mean number of photons contained in the light pulse, n_{ST} actually coupled into the single mode fiber optic amplifier. The lower limit, *a*, was generally taken as 0.001 for weak turbulence where $P_B(\hat{I} = 0.001) << 10^{-9}$ but was decreased to 10^{-7} for stronger turbulence levels where $P_B(\hat{I} \approx 0) >> 10^{-9}$. The step size, $\Delta\hat{I}$, in the numerical evaluation of (6) was kept sufficiently small so that the argument of the erfc(-) function in (2) changed by less than 0.1 at each step of the integration. The upper limit, *b*, is set by the rate of decrease of the erfc(-). At low turbulence, *b* was greater than 1, typically 2 or 3, whereas at stronger turbulence, *b* was typically less than 0.01 due to the large values of n_{ST} required to obtain a BER of 10^{-9}. At low turbulence levels, typical direct detection receiver performance is shown in Figure 7a with the Beckman pdf shown in Figure 7b.

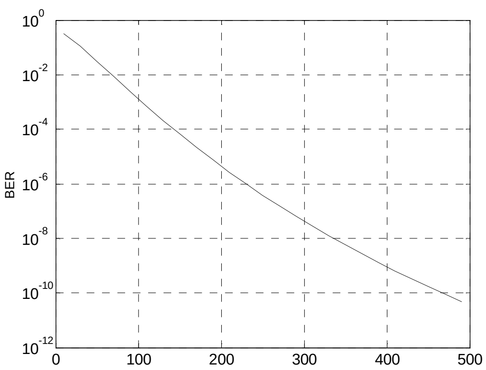

Fig. 7a. BER as a function of n_{ST} for l_0 / R_F =0.5 and σ_{Rytov}^2 =0.06, the same conditions as Fig. 5.

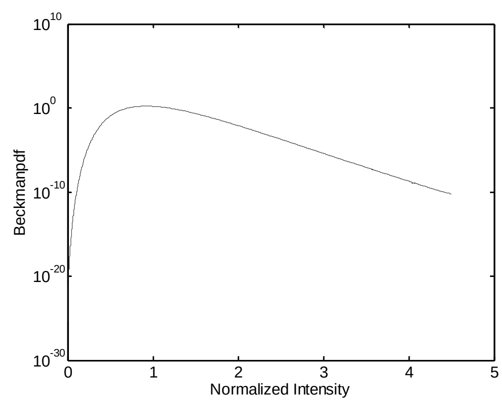

Fig. 7b. $P_B(\hat{I})$ as a function of $\hat{I}$.

Because of the relatively small values of n_{ST} in Figure 7, both the leading and falling tails of the Beckman pdf contribute to the average BER. Under stronger turbulence conditions, the BER and Beckman pdf are as shown in Figures 8a and 8b. Fig. 8b shows only the leading edge of the Beckman pdf as it is the only region of the pdf to significantly contribute to the low values of the BER due to the rapid decrease of the erfc(-) with $n_{ST}\hat{I}$. Note that the value of n_{ST} required to produce a BER of 10^{-9} has increased from about 400 to 2 x 10^7 or by five orders of magnitude due to the exponential nature of the Beckman pdf.

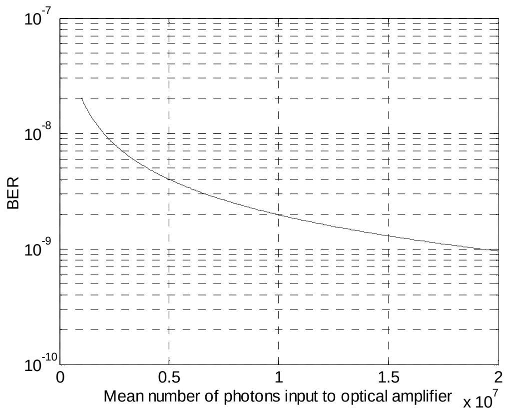

Fig. 8a. BER as a function of n_{ST} for l_0 / R_F =0.5 and σ^2_{Rytov} =0.40.

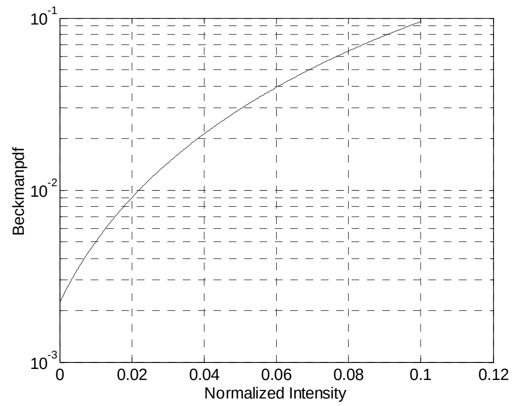

Fig. 8b. $P_B(\hat{I})$ as a function of $\hat{I}$.

The results of direct detection receiver performance are summarized in the 3D plot of Figure 9 which shows the value of n_{ST} required to obtain a BER of 10^{-9} for a point photodetctor as a function of l_0 / R_F and σ^2_{Rytov} . A typical value of link distance is 1-5 km and daytime values of C_n^2 are typically 1-10 x 10^{-14} $m^{-2/3}$. At the telecommunications wavelength of 1.55 μm, the Fresnel zone size is 1.5-3.5 cm. Assuming l_0 varies between 1.0 mm and 1.0 cm, the parameter l_0 / R_F varies between 0.03 and 0.7. For initially spherical waves, the Rytov variance varies between 0.08 and 0.8. The vertical axis is in dB, i.e. $10\log_{10}(n_{ST})$. As can be seen, the required average number of photons per pulse coupled into the optical amplifier increases by tens of dB as the Rytov variance increases from 0.06 to 0.4 which is still considered relatively weak turbulence. The rapid increase is primarily due to the exponential character of the Beckman pdfs of a point receiver. Interestingly, receiver sensitivity actually improves by about 3 dB as l_0 / R_F decreases from 0.12 to 0. This is an “inner scale” effect on the BER. Performance at larger values of Rytov variance was not computed because the value of n_{ST} became so large that it would saturate the optical amplifier. At 80 dB, n_{ST} =10^8 photons and corresponds to a peak intensity of 13 mW for a 1 ns rectangular light pulse at λ = 1.55 μm. The data shown in Figure 9 were obtained under the conditions of an ideal optical amplifier (n_{SP} =1.0) with gain G = 1000, and ideal modulator, ε =0, one hundred temporal modes, B_0T = 100, and 1 ns rectangular laser light pulses. Under these conditions, a BER of 10^{-9} could be obtained with about 400 photons coupled into the single mode fiber optic amplifier under the conditions of σ^2_{Rytov} =0.06 and l_0 / R_F =0.70. Cross sections of the 3D receiver performance surface of Figure 9 are shown in Figure 10 with l_0 / R_F as a parameter.

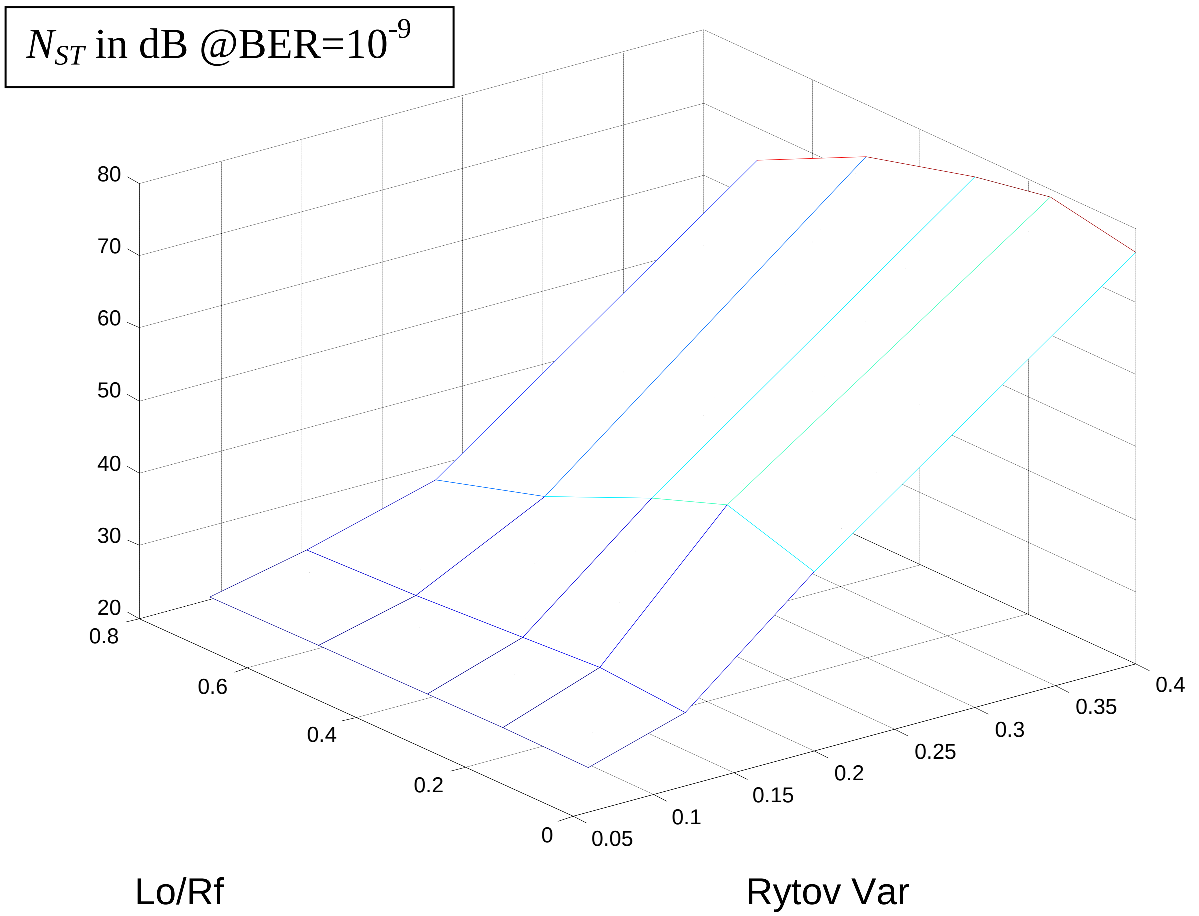

Figure 9. Direct detection receiver sensitivity as measured by average number of photons coupled into optical amplifier required to produce a BER =10^{-9} with l_0 / R_F and σ^2_{Rytov} as parameters.

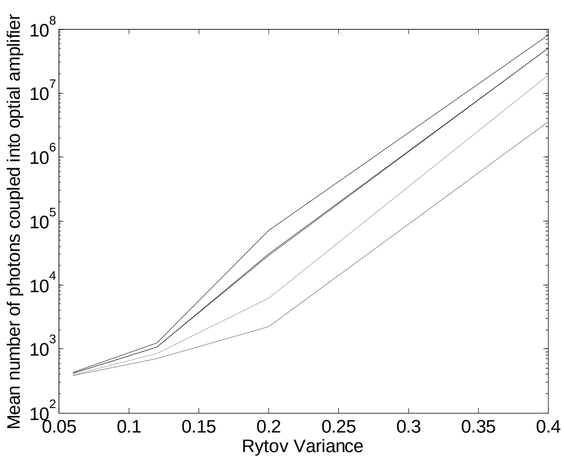

Figure 10. Receiver sensitivity as a function of Rytov variance for l_0 / R_F = 0.16, (top), 0.0, 0.30, 0.50, and 0.70 (bottom) as a parameter.

Figures 9 and 10 show that the receiver is most sensitive at the larger values of l_0 / R_F and smallest values of σ^2_{Rytov}. They also indicate that a focusing lens must be used to couple light into the fiber optic amplifier to both reduce the level of intensity scintillations to an acceptably low level *and* to minimize the exponential nature of the pdf of $\hat{I}$. In one sense, the function of the lens is to minimize the probability that $\hat{I}$ =0 which it does by producing a pdf($\hat{I}$) that is very close to log-normal at the focal point of the lens. The lens must also match the received optical field profile to that of the single mode fiber amplifier.

Any departure from the ideal conditions assumed above will of course lead to a loss in receiver sensitivity, with only a decrease in the number of temporal modes leading to an improvement. An important loss comes from an imperfect retro-modulator extinction ratio. Figure 11 plots receiver BER under the same conditions as Figure 7 except that the modulator extinction ratio is assumed to be 5:1, or ε = 0.2. In order to produce a BER of 10^{-9}, n_{ST} has increased to about 600 photons which corresponds to a loss in sensitivity of 1.7 dB. Increasing the noise figure of the optical amplifier to F =4.5 dB, (n_{SP} = 1.4), contributes about another 1.5 dB of loss in receiver sensitivity.

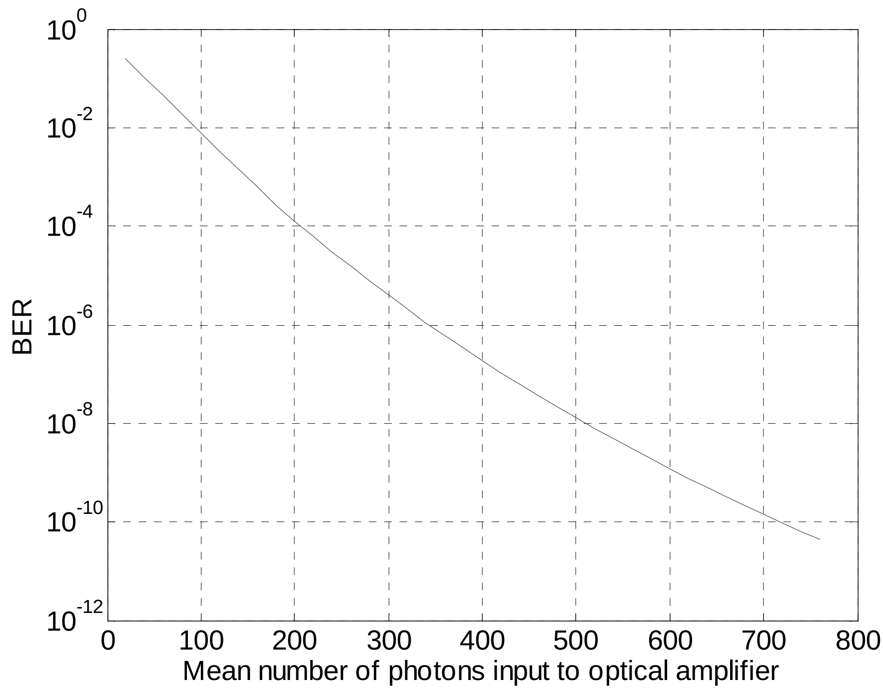

Fig. 11. BER as a function of n_{ST} for l_0 / R_F =0.5 and σ^2_{Rytov} =0.06 for a modulator extinction ratio of 5 (ε = 0.2).

Finally, the performance of the coherent receiver in Figure 2 was computed for the same conditions of Figures 7. The results are shown in Figure 12 which represents the performance of an ideal asynchronous receiver for perfect ASK signaling and a local oscillator laser power sufficiently strong to ensure the receiver operates in its shot noise limited regime. The performance of a nonideal receiver will of course be worse, so the performance curves for it will lie to the right of the ones shown. Figure 12 shows that the ideal, shot-noise limited asynchronous coherent receiver outperforms the direct detection receiver by about 7.5 dB. At more severe turbulence levels, the performance advantage increases to about 10 dB.

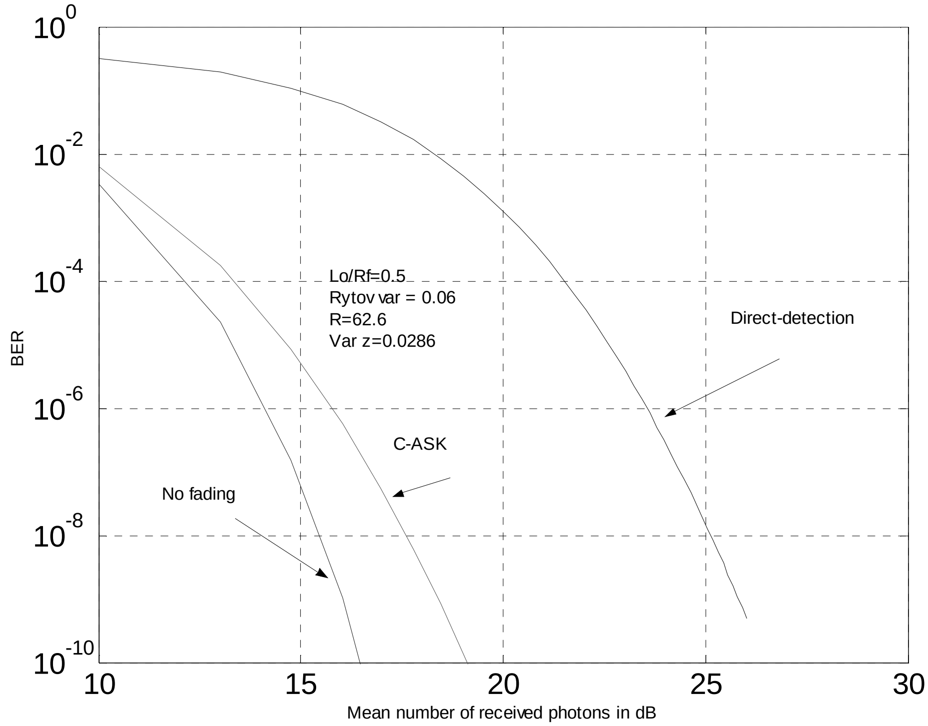

Figure 12. BER performance for asynchronous coherent ASK receiver of Figure 2 for (a) no atmospheric fading, (b) atmospheric fading with l_0 / R_F =0.5, σ^2_{Rytov} =0.06, σ^2_z =0.0286, R=62.6, and $\sigma^2_{\ln \hat{I}} = 0.06$, and (c) direct detection receiver of Figure 1 with same parameter values.

5. CONCLUSIONS

The analyses presented here indicates that the use of an optical pre-amplifier with a gain of 30 dB in a direct detection optical receiver for a free-space atmospheric optical communication link with a short pulse laser yields a BER of 10^{-9} at receiver sensitivities corresponding to a few thousand received photons coupled into the single mode optical amplifier input port provided that atmospheric turbulence levels are not too large and that the optical pulse duration and optical bandpass filter are such that only 100 temporal modes are coupled into the receiver electronics. The analysis was performed using a Beckman pdf to describe the intensity fading statistics and illustrated the effects of inner scale size of the atmospheric turbulence on receiver performance. Any practical system must use a focusing lens of sufficiently large diameter that near log-normal intensity fading is produced at the focal point of the lens in order to overcome the effects of substantial atmospheric turbulence levels. The lens effectively does this by collecting enough of the received scintillation pattern to render the value of the probability density for the normalized intensity scintillations at $\hat{I} = 0$ at the focal point of the lens ideally zero (the value for log-normal fading statistics), but certainly as small as possible for a given lens size and atmospheric turbulence conditions. Given the complexity of the Beckman pdf and the limitations of analytic treatments of atmospheric turbulence, it does not appear at this time to be possible to predict analytically the size of the lens required to guarantee a given level of BER performance as a function of the turbulence conditions. Accurate experimentally obtained data for Gaussian beams propagated through atmospheric turbulence (or simulated data using proper phase screens) would be extremely useful in quantifying the effect of lens size on the form of the pdf for $\hat{I}$ for these types of receivers. Coherent optical receivers would, in principle, produce a 7 to 10 dB improvement in sensitivity. In practice, the improvements will be less but probably significant, greater than 3 dB.

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